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NAVAL IN-PLACE SEAFLOOR SOIL TEST EQUIPMENT: A PERFORMANCE EVALUATION

By

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ABSTRACT

The Naval Civil Engineering Laboratory (NCEL) has developed a vane shear and cone penetrometer apparatus capable of obtaining the in-place undrained shear strength of sediments to a depth of 10 feet in the seafloor. The device is a subsystem of the Deep Ocean Test In-Place and Observation System (DOTIPOS). Information obtained with this equipment will enhance the Navy's ability to design foundations more economically and reliably for seafloor installations. The results of tests performed at 100- and 600-foot deep sites and the evaluation of DOTIPOS and the vane shear and cone penetrometer apparatus are presented.

The DOTIPOS-mounted vane shear and cone penetrometer apparatus operates satisfactorily to water depths of 600 feet and produces results which appear reasonable when compared to previous theoretical and laboratory experimental results. Laboratory and in-situ vane shear results are in reasonable agreement; however, the in-situ results exceed the laboratory results by 10 to 20 percent. A relationship between percent clay content of the sediment and the ratio of cone resistance to vane shear strength appears feasible for seafloor sediments. Verification of this relationship will establish the cone penetrometer as a more useful and economical site survey tool.

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INTRODUCTION

Subject and Purpose of Report

This report describes the development and the evaluation by the Naval Civil Engineering Laboratory (NCEL) of a seafloor soil testing device capable of performing vane shear and static cone penetrometer tests to a depth of 10 feet into the seafloor. Data are presented from tests with this equipment at two seafloor locations. The program was sponsored by the Naval Facilities Engineering Command. The overall objective of this program was the development of a device with associated test procedures with which the in-situ strength characteristics of seafloor sediments may be determined to a sediment depth of 10 feet at water depths to 6,000 feet. The device will be employed to generate data which will enhance the Navy's ability to design and construct foundations for seafloor structures.

Background

The design of foundations for Naval seafloor installations requires detailed information on the strength properties of seafloor sediments as they exist in situ. Present information for seafloor foundations has come from the laboratory analysis of marine sediment cores. The present sampling techniques, however, are known to disturb the soil and provide a poor engineering sample for a sophisticated laboratory analysis. In addition, most laboratory analyses have been performed by geologists and oceanographers with little regard for the sediment's foundation-supporting properties. Consequently, seafloor foundations have been designed with a high factor of safety, a procedure which is unnecessarily expensive. Sometimes the intended high factor of safety may, in actuality, be dangerously low because of unknown or unanticipated conditions.

For more precisely designed seafloor foundations, improved techniques should be developed to obtain more accurate design data. Two alternatives are possible: (1) develop improved soil sampling equipment and laboratory test techniques or (2) develop equipment to determine the engineering strength properties of sediments in situ. It is apparent that neither of these approaches is sufficient by itself for all design applications. However, information which is obtained in situ is valuable for foundation design, and it may be used to evaluate the accuracy of laboratory data derived from the analysis of core samples, and vice versa. This program is concerned only with the development of an in-situ test device capable of obtaining the vane shear strength

and static cone penetrometer resistance of seafloor soils. Future efforts will be concerned with the improvement of soil sampling equipment and laboratory test techniques that complement in-situ test data. The overall program will provide the Navy Engineer with much greater test flexibility, and with the ability to measure many different soil responses and thereby increase design efficiency.

The vane shear and static cone penetrometer test devices were chosen because of their reliability, simplicity and widespread popularity for testing saturated terrestrial soils. The devices have been used successfully on terrestrial soils to determine the undrained shear strength of soft saturated soils. For structures founded on soft saturated soils, the initial loading conditions are critical; the effective soil stress due to high excess pore pressures is at a minimum, and the potential for shear failure is the greatest. The vane shear tool and static cone penetrometer will determine shear strengths under conditions duplicating initial foundation loads. Seafloor soils are expected to behave in many ways similar to soft saturated terrestrial soils; therefore, the vane shear and static cone penetrometer should be equally applicable for determining the critical support load.

Terrestrial field vane shear tests consist of forcing a four-bladed vane into the soil, usually from the bottom of a bore hole, or hand-driven from the surface with a sledge hammer. At the desired depth, the vane is rotated at a constant angular velocity, and the torque required for rotation is recorded as a function of angular displacement. The peak torque measured is related to the undrained shear strength of the soil by assuming (1) that the soil fails along a surface having the shape of a cylinder with diameter and height equal to the width and height of the vane, and (2) that there is essentially no flow of water into or out of the failure zone during the course of the test. Including full shear of the vane top and bottom, and assuming that the undrained shear strength is completely mobilized across each end, the governing equation is

$$S_u = \frac{6T}{\pi W^2 (3H + W)} \tag{1}$$

where S_u = undrained soil shear strength

T = peak vane torque

W = vane width

H = vane height

The field vane shear test was developed in Sweden in the late 1940's and has been used extensively in Scandanavia and Great Britain to investigate both unstable slopes and bearing capacity failures of

foundations involving soft or sensitive clays. Primarily because of the assumptions of undrained shear and of disturbance during vane insertion, the vane shear test has not been used to any great extent on pervious silts and sands. The field vane shear, however, appears to be well suited for the analysis of seafloor sediments and has been used in several limited studies (Dill and Moore, 1966; Richards, 1969). It appears to be preferable to the cone penetrometer test because the failure pattern is more accurately known. The greatest limitation of the vane is its inability to test coarse-grained sediments.

The cone penetrometer test consists of forcing an inverted circular cone into the ground usually at a constant rate of penetration. The cone is generally forced in from the surface, although it is possible to begin a test at the bottom of a bore hole. The force applied to the cone is recorded as a function of depth.

The cone penetrometer test has been used in Europe since the 1930's. It has been particularly emphasized in the Netherlands and is often referred to as the Dutch cone test. The results of cone tests have generally been used in empirical relations for the control of highway and railroad embankment construction and the design of pile foundations. In these cases, the shear strength of the soil is not determined; the cone resistance is used directly in the control or design process. Since the penetrometer progresses into the sub-soil by mobilizing the soil's shearing resistance, it should be possible to evaluate the shear strength in terms of the penetration test results. However, in certain instances the test results may be difficult to analyze because of the data scatter and the soil-type dependency. In general, the major advantages of the cone penetrometer test appear to be (1) its economy and (2) its capability of testing soils such as loose sands and sensitive clays which could not be sampled and tested in the laboratory.

Approach and Scope

The Deep Ocean Test In-Place and Observation System (DOTIPOS) (Figure 1) is a remotely controlled bottom platform that was developed for controlled placement and observation of instrumented packages at an undisturbed seafloor site to water depths of 6,000 feet. The vane shear and static cone penetrometer tower, a subsystem of DOTIPOS, was developed specifically to obtain the in-situ shear strength of marine sediments to a depth of 10 feet. The in-situ test tower is also operable to water depths of 6,000 feet.

This report presents the results of vane shear and static cone penetrometer tests obtained with DOTIPOS at a 100-foot seafloor site and a 600-foot seafloor site. The data from both sites are analyzed, and the results are compared with empirical test parameters obtained for similar terrestrial soils. A performance evaluation of DOTIPOS and the vane shear and static cone penetrometer subsystem is also presented.

TEST APPARATUS

General

DOTIPOS is a complete system which may be used as a support tool for either a seafloor investigation or the controlled emplacement of an object on the bottom. The DOTIPOS system (Aetron, 1968) is comprised of several major components and support components, including the DOTIPOS platform (Figure 2), the support-telemetry cable, the surface control instrumentation, and a winch system.

The configuration and electronics of DOTIPOS are suitable for supporting one or more subsystems to be used for a specific seafloor mission. One subsystem of DOTIPOS is the vane shear and cone penetrometer apparatus used in this in-situ soil test program.

DOTIPOS System

Description of the Platform. A detailed photograph of the DOTIPOS platform with the vane shear and cone penetrometer tower is presented in Figure 2. The superstructure of the platform is pyramidal shaped with an 18-foot square base and a height of 17-feet 6-inches. The platform is designed to operate on the seafloor to a depth of 6,000 feet. It weighs approximately 6,000 pounds in air and approximately 2,000 pounds in water. Three 4- by 4-foot pads support the DOTIPOS platform distributing the load over a large area. The bearing pressure is less than 50 psf.

The platform is constructed of welded structural aluminum subassemblies which bolt together. The subassemblies include four welded structural aluminum pipe side sections, four corner assemblies, four bumper spring assemblies and miscellaneous superstructure members.

Several elements are attached to the superstructure (Figure 2) to support the operation of the platform or control the operation of a subsystem. Closed circuit TV and 16 mm cameras are provided to observe and monitor any specific test or emplacement. The TV and 16 mm cameras which are attached to a pan and tilt unit provide omni-directional viewing on the seafloor. Two underwater lights are used to illuminate the test operations. A pinger is included to assist either the placement of the platform on the seafloor or recovery of the platform if lost. Electrical power is regulated and transmitted by the transformer, electronics sphere, and interconnecting underwater cable assemblies. All of the electrical components are encased in either pressure resistant or pressure-equalizing container for protection and trouble-free operation.

Support-Telemetry Cable. The DOTIPOS platform is supported by and the elements are controlled through a combination support-telemetry cable. The cable is approximately 8,150 feet long and 1.116 inches in diameter, and it is rated to support 45,000 pounds. While submerged, the submerged weight of the cable is one pound per linear foot. The cable provides transmission of 2400 VAC, single phase, 60 Hz power at 20 KVA directly into the underwater transformer.

Surface Control Instrumentation. Control instrumentation is placed in an 8-foot wide by 12-foot long instrument van for protection. The control instrumentation (Figure 3) is used to regulate the elements attached to the platform, to permit a visual observation of the performance of the elements, and to present a permanent record of the subsystem feedback. A 40-channel Pulse Duration Modulation (PDM) system provides for the down-link control of the platform elements and the subsystem(s). A 20-channel digital PDM up-link control system gives positive readouts at the control console of the condition of the submerged components. In addition to the digital PDM control and readout system, an Inter-Range Instrumentation Group (IRIG) FM carrier system was provided to permit 14 channels of underwater transducer feedback to be recorded; however, only four channels of data were used for the vane shear and cone penetrometer tests; i.e., axial load, vertical displacement, torque and rotation, as appropriate.

Vane Shear and Cone Penetrometer Subsystem

Description of the Tower. The vane shear and cone penetrometer tower (Figure 2) is mounted on the DOTIPOS platform as an accessory, and it is remotely controlled from the surface instrument van. The 2-inch diameter penetration rod is mechanically pressed into the soil by an electrical motor and jack-screw system. The penetration rod is inserted or withdrawn at a rate of 10 inches per minute. Another electrical motor and transmission system is used to rotate the penetration rod at a rate of either 10 rpm or 1 rph (6 deg/min). Potentiometers are used to monitor both displacement and rotation of the penetration rod.

Load Cell. A load cell (Figure 4) is coupled to the bottom of the tower penetration rod so that torque and axial load may be recorded for the field vane and cone penetrometer. The load cell was designed to measure a torque of 0 to 500 in.-lbs and an axial force of 0 to 2,000 lbs. It consists of an enclosed 1/2-inch diameter steel rod which is instrumented with strain gages. Two single gages were placed along the axis of the rod to measure axial load, and two 90-degree rosettes were placed on the rod at 45 degrees to measure torque. Additional gages were added for temperature compensation.

Vane Shear and Cone Penetrometer Tools. Either a vane shear tool or a cone penetrometer tool may be attached to the load cell. A drawing of each tool and significant dimensions are presented in Figure 5. All of the tools were fabricated from stainless steel.

The shear vane consists of four thin rectangular blades which are welded at 90 degrees to a circular shaft. A height-to-diameter ratio of 2.0 was used for all four vanes. The four vane diameters are 2, 2½, 3, and 4 inches.

The cone penetrometer tool used for all tests is an inverted right circular cone with a projected area of four square inches. It was designed with a vertical lip to prevent soil from clogging the space between the cone and transducer and thereby affect axial load measurement. Because of this vertical surface area, cone resistance, recorded as axial load, is partially comprised of frictional resistance or adhesion on this vertical surface. Since the maximum anticipated frictional effect is less than 5 percent, it will be neglected.

Winch System

The winch, which is used to raise and lower the DOTIPOS platform, consists of three units: a diesel-driven power unit, a dual-drum traction winch, and a single-drum storage unit. Each of these units is mounted separately as shown in Figure 6.

The power unit hydraulically drives both the traction and storage units, weighs about 8,500 pounds, and has approximate dimensions of 4- by 10- by 9-feet high. The unit is driven by a diesel engine which develops 245 bhp at 1,965 rpm.

The dual-drum traction unit provides for hoisting and controlled payout of cable. It weighs about 11,500 pounds with approximate dimensions of 6- by 8- by 6-feet high. The traction unit develops line pulls of 20,000 pounds at 200 fpm and 1000 pounds at 400 fpm and has a 2500-pound line pull braking capacity.

The single-drum storage unit has the function of stowing the lifting-telemetry cable. The storage unit weighs approximately 8,500 pounds and has dimensions of 8- by 10- by 7-feet high. A spooling device is provided to lay cable on the drum in an orderly manner. Electrical power and telemetry are transmitted through the storage unit by a slip-ring mechanism.

GENERAL TEST PROGRAM AND PROCEDURES

A total of eight sets of vane shear and nine static cone penetrometer tests were performed at two seafloor test sites. Both sites were located in the Santa Barbara Channel off the coast of Southern California (Figure 7). The geographic coordinates of the center of the 100-foot Pitas Point Site (Site 1) are: 34^o 16.7'N and 119^o 24.2'W and of the center of the 600-foot SEACON Site (Site 2) are: 34^o 15.0'N and 119^o 44.0'W. The program of vane shear and cone penetrometer tests performed at each site is presented in Tables 1 through 4. The tests are listed in chronological order for each tool.

Table 1. Program for vane shear tests at Site 1.

Test No.	Soil Condition	Vane Width and Height (in)	Maximum Test Depth (ft)
PP-V1	Undisturbed	3 x 6	3.25
PP-V2	Undisturbed	3 x 6	5.25

Table 2. Program for vane shear tests at Site 2.

Test No.	Soil Condition	Vane Width and Height (in)	Maximum Test Depth (ft)
SCN-V1	Undisturbed Remolded	3 x 6	6.0 .66
SCN-V2	Undisturbed Remolded	2½ x 5	7.25 6.25
SCN-V3	Undisturbed Remolded	2 x 4	7.5 7.5
SCN-V4	Undisturbed Remolded	2 x 4	5.75 4.75
SCN-V5	Undisturbed Remolded	4 x 8	1.25 None
SCN-V6	Undisturbed Remolded	4 x 8	3.33 1.33

Table 3. Program for static cone penetrometer tests at Site 1.

Test No.	Maximum Test Depth (ft)
PP-C1	9.25
PP-C2	9.25
PP-C3	9.75

Table 4. Program for static cone penetrometer tests at Site 2.

Test No.	Maximum Test Depth (ft)
SCN-C1	9.0
SCN-C2	9.25
SCN-C3	9.1
SCN-C4	9.66
SCN-C5	9.0
SCN-C6	9.25

Upon arrival at the test site, the ship was anchored in a two-point (bow-stern) moor with the aid of a LORAC B positioning system. The ship was directed into the surface current to reduce lateral drift. The LORAC B records show that the ship did not drift more than 40 feet at each test site.

DOTIPOS was prepared for the first test series by attaching either the vane or cone. The hoist lines for DOTIPOS were then connected to the ship's deck crane, and DOTIPOS was lifted over the side of the ship. At a water depth of 15-20 feet, the DOTIPOS support-telemetry cable was made taut, and the load on the deck crane was relieved. SCUBA divers were used to detach the DOTIPOS hoist and handling lines from the deck crane. DOTIPOS was then lowered to the bottom, and extra support-telemetry cable was provided to prevent test disturbance from ship drift.

Two or three cone penetrometer tests were normally performed consecutively. Figure 8 shows the cone penetrometer on the ship's deck in its test ready position. From the surface control cabin, the vertical displacement of the cone penetrometer was controlled, and the displacement and axial cone load were monitored on an oscillograph recorder. Proper test performance requires use of the TV camera. The television camera is an invaluable visual aid in that it allows the operator to accurately position the cone on the sediment surface prior to initiating each cone penetrometer test. Without the camera, penetration readings could be off by several inches due to settlement of the reference platform (DOTIPOS). The surface sediment is very soft and cone penetration could initially go undetected. After each test, DOTIPOS was lifted approximately 20 feet above the seafloor and repositioned over an undisturbed patch of soil. The remainder of the cone penetrometer tests were performed according to this procedure, and DOTIPOS was returned to the deck of the support ship.

The cone penetrometer tool was replaced with a vane shear tool in preparation for the vane shear tests. DOTIPOS was returned to the seafloor and positioned for a set of vane shear tests. (Each set of vane shear tests consists of individual tests at incremental depths in the soil profile.) From the surface control cabin, the vane tool, shown on the ship's deck in Figure 9, was pressed into the soil in increments of 1 foot. As with the cone test, the TV camera is used to accurately position the vane on the sediment surface. At each increment, the vane was rotated in the undisturbed soil at 1 rph (6 deg/min) until a peak shearing resistance was recorded on the oscillograph; the peak shear strength usually occurred within 3 to 5 minutes. The remolded shear strength was then obtained by rotating the vane one revolution at a high angular velocity (10 rpm), stopping vane movement for one minute, and continuing the test at the slow angular velocity (1 rph). The final depth of each test was limited by either the maximum displacement of the vane shear device (10 feet) or a soil which prevented maximum penetration.

DOTIPOS was then returned to the water surface where SCUBA divers either cleaned the soil that adhered to the vane tool or changed the size of the vane tool. DOTIPOS was returned to the seafloor and repositioned for additional testing according to the above appropriate procedure before being returned to the ship's deck.

EVALUATION OF DEVICE PERFORMANCE

DOTIPOS, with the vane shear and cone penetrometer subsystem, was found to operate quite satisfactorily at the 100- and 600-foot deep test sites.

Several sets of vane shear tests and cone penetrometer tests may be performed during an eight-hour work day. It takes approximately 20 minutes to transport DOTIPOS from the deck to the seafloor and the same time to return it to the deck at the 600-foot test site. With DOTIPOS on the seafloor, a set of vane shear tests at one-foot intervals may be performed on an average of about one each 90 minutes, and a cone penetrometer test may be performed in about 25 minutes.

The tests were performed from a U. S. Navy ARS and a U. S. Navy LST. Both ships have ample deck space to hold the DOTIPOS structure and winch system. Many ships, such as the AGOR class, have neither the deck space to set up the three units of the winch system nor a crane capable of lifting the DOTIPOS platform. The load handling of the DOTIPOS platform from the ARS and LST was no problem when the wave height was less than 5 feet.

Problems which occurred during the sea trials were of a minor nature. The more notable problems include (1) bent vane shear tools, (2) shear pin failure in the television camera pan and tilt unit, and (3) hydraulic seal failure to electrical components. All of the problems were easily recognized and corrected. With these various modifications, the quality and reliability of DOTIPOS and the vane shear and cone penetrometer subsystem was significantly enhanced.

TEST RESULTS

Results from the tests performed in the Laboratory and in situ on Site 1 (Pitas Point 100-foot test site) and Site 2 (SEACON 600-foot test site) sediments are presented in the following paragraphs. All vane shear data were reduced according to Equation 1 (Introduction).

Site 1

Soil Properties. Several cores were taken at Site 1. A comparison of previously obtained core data (Kretschmer, 1967) with data retrieved from core samples obtained in conjunction with the vane shear, cone penetrometer evaluation indicates that Site 1 sediment has good areal uniformity. Therefore, only typical laboratory results from one core will be presented. A Ewing-type gravity corer was used.

Natural water content, Atterberg limits, effective pressure (effective unit weight x depth), laboratory vane shear strengths, ratio of shear strength to effective pressure, sensitivity and liquidity index are presented in Figure 10. Laboratory analyses were performed according to standard specifications (ASTM, 1964). According to the Trilineal Oceanic Soil Classification Chart (Shepard, 1954), the sediment taken from Site 1 is classified as a clayey silt; however, according to the Unified Soil Classification System (WES, 1960), the sediment varies from a clayey silt (ML) to a silty clay (CL) (Table 5). This discrepancy is not surprising because the Unified System is based on grain size and plasticity where as the Trilineal System is based strictly on grain size. The sediment is fairly insensitive (low ratio of undisturbed vane shear strength to remolded strength) with values generally from 1.5 to 2.5 and exhibits liquidity indices that denote a loosely deposited material.

Table 5. Classification of soil at Site 1.

Classification System	Depth - Inches			
	9-12	21-24	33-36	45-48
Unified Soil Classification	ML	ML	CL	ML
Trilineal Soil Classification	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt

Laboratory vane shear strength data taken from Figure 10 were superimposed on a plot of laboratory vane shear strength data (Figure 11) previously obtained in conjunction with the evaluation of the in-situ plate bearing device (Kretschmer, 1967). There exists a certain amount of data scatter, but data from Core PP-1 follow the same general trend as the previous results. Since the data are limited and the core samples probably disturbed, it is unrealistic to make any definite conclusions regarding the sediment behavior.

In-Situ Test Data. Data from the cone penetrometer and vane shear tests at Site 1 are presented versus depth in Figures 12 and 13. A total of three cone penetrometer tests and two sets of vane shear tests were performed.

The original cone test data were reduced to straightline plots of unit cone load for the projected cone area versus depth in the sediment (Figure 12). The three cone penetrometer plots show small discontinuities

Table 6. Soil Classification for Site 2 Core No. SCNI—37.

Classification System	Depth-Inches												
	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24	24-27	27-30	30-33	33-36	36-39
Unified Soil Classification	ML	ML	ML	ML	ML	MH	MH	MH	MH	MH	ML	ML	MH
Trilineal Soil Classification	Silty Sand	Silty Sand	Sand Silt Clay	Sand Silt Clay	Sand Silt Clay	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt

Table 7. Soil classification for Site 2 Core No. SCNI—49.

Classification System	Depth-Inches											
	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24	24-27	27-30	30-33	33-36
Unified Soil Classification	ML	ML	CH	ML	MH	MH	MH	MH	MH	MH	MH	MH
Trilineal Soil Classification	Silty Sand	Silty Sand	Sand Silt Clay	Sand Silt Clay	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt	Clayey Silt

in unit cone load with depth that probably result from layering. However, the general duplication of test results is quite satisfactory. The results indicate an increasing cone load with depth between about 10 inches and 80 inches, and a stiff layer of soil was encountered beyond 80 inches.

The vane shear test data are presented (Figure 13) as undisturbed shear strength versus depth to the vane center. Only two sets of tests were performed with the shear vane before mechanical difficulties were encountered with the transducer. A line of best fit is placed between the data points. The data show an approximate linearly increasing shear strength with depth to about 80 inches where a stronger soil layer is again encountered. The presence of the stiff layer reinforces the results of the cone penetrometer tests.

Site 2

Soil Properties. Eight short cores were taken within 500 feet of Site 2 by means of a Ewing-type gravity corer. Laboratory analysis of the cores indicates that Site 2 sediment has good areal uniformity. Data from two of the more thoroughly analyzed cores are presented in Figures 14 and 15. The grain size distributions are seen to change uniformly with depth. From Tables 6 and 7 the soil classification, according to the Unified Soil Classification System, generally varies from a clayey silt of low plasticity (ML) to a clayey silt of high plasticity (MH); however, when classified by the Trilineal System, the sediment varies from a silty sand to a clayey silt (Tables 6 and 7). It should be emphasized that grain size alone (Trilineal System) is not sufficient to specify soil behavior. For engineering purposes, the Unified Soil Classification System presents a more accurate definition of a soil's engineering behavior.

As at Site 1, the sediment is fairly insensitive (low ratio of undisturbed vane shear strength to remolded vane shear strength) with sensitivities averaging between 1.5 and 2.5. Also, the high liquidity indices (greater than one) indicate a loosely deposited or somewhat unconsolidated sediment in the top three feet of the seafloor. Further analysis showed that the average organic carbon content is 0.5 percent and the average carbonate content is 1.0 percent.

Laboratory vane shear data taken from the eight Site 2 core samples are plotted on Figure 16. The line of best fit for the average shear strength-depth relationship generally appears to increase uniformly with depth to 3 feet. There is a significant amount of scatter in the data; however, this is attributed primarily to disturbance during core sampling and transporting and soil inhomogeneity.

In-Situ Test Data. Data from Site 2 are presented in Figures 17 through 20. A total of six cone penetrometer tests and six sets of vane shear tests, including both undisturbed and remolded tests, was performed.

The cone penetrometer test data (Figures 17 and 18) show excellent replication between all six tests; the six tests were plotted as two figures to prevent clutter. The characteristic small unit cone load discontinuities are present as on previous cone penetrometer test records. The test results reveal a somewhat stiff soil layer between 10 and 20 inches after which the cone load tends to increase linearly with depth.

A plot of peak undisturbed vane shear strength versus average penetration depth is presented in Figure 19. Even though considerable data scatter exists, there is a noticeable trend shown by the line of best fit. The results of test SCN-V6 are not valid because water leaked into the load cell. It is interesting to note that a stiff soil layer is not present between 10 and 20 inches as exhibited on the cone penetrometer load profile. In fact, low vane shear strength values are encountered in the top 20 inches of soil. A linearly increasing shear strength is encountered beyond 20 inches. The strength increase for the remolded soil (Figure 20) is linear with depth to 90 inches; however, the rate of increase is not as great as for the undisturbed soil.

ANALYSIS

Comparison of Laboratory and In-Situ Vane Data

The estimated laboratory and in-situ vane shear strength-depth relationships for Site 1 and Site 2 sediment are presented in Figures 21 and 22. There is reasonable agreement between the laboratory and in-situ results; however, for both sites the in-situ vane shear strengths exceed the laboratory strengths. There are many factors which could influence the laboratory and in-situ vane shear test results and cause this disagreement.

<u>Shear Rate</u>. Laboratory and in-situ vane tests are both performed at rotational velocities of 6 deg/min; however, actual shear rates differ. Shear rates vary in direct proportion to vane blade width. The in-situ vanes used vary from four to eight times larger than the laboratory vanes, therefore in-situ shear rates can be four to eight times faster than laboratory test rates. The faster in-situ test shear rates could result in higher shear strengths due to viscous effects introduced by shearing the soil rapidly. However, the slower laboratory shear rates could also result in higher shear strengths due to partial drainage. Skempton (1948) performed in-situ vane shear tests in a soft clay at shear rates varying by as much as a factor of 50. His conclusion was that in normal testing practice, the influence of shear rate is not of the first importance. According to Skempton's test results, the variation in NCEL test data due to shear rate effect should not exceed 2 percent.

Soil Disturbance. Soil disturbance affects both laboratory and in-situ vane shear test results. However, disturbance effects are considered to be more severe in laboratory testing. Laboratory vane strength data are affected by sampling disturbance and also by disturbance caused during vane insertion, while soil disturbance during in-situ vane testing is limited to disturbance caused by vane insertion. The degree of soil disturbance caused by vane insertion is related to the area of the vane divided by the area of a cylinder generated when the vane is rotated about its axis. To minimize soil disturbance due to vane insertion, all laboratory and in-situ vanes have area ratios less than the recommended maximum value of 0.15 (Brand, 1967).

It is probable that the greatest errors in laboratory testing are generated by soil disturbance which originates from poor sediment sampling techniques. In the field of seafloor soil mechanics, it has been difficult to obtain good quality sediment samples, primarily because all of the samplers were designed for geological investigations with little emphasis on preserving the sediment engineering properties.

Friction on the Torque Rod. The in-situ vane shear assembly was designed to minimize the effect of friction or adhesion on the torque rod. The torque rod diameter is small in relation to the vane width and the torque rod length between the vanes and transducer is small. However, the torque rod lengths are such that the transducer does not interfere with the failure surfaces generated by vane rotation. The torque produced by friction or adhesion on the torque rod is estimated at less than 2 percent of the total torque. Therefore, the actual vane shear strengths may be 2 percent less than those measured with the NCEL test device. A similar error is expected in the laboratory vane shear test results because a portion of the torque rod is immersed in the soil during shear.

Since laboratory and in-situ test results are both somewhat equally affected by friction on the torque rod, the discrepancies in the strength data are probably not due to torque rod friction. Also, it is most likely that data scatter is sufficient to mask a 2 percent error in strength data.

Correlation of Vane and Cone Results

A comparison of the cone penetrometer and vane shear test results is presented in Figure 23 for Site 1 and Site 2; the ratio of average unit cone load to average vane shear strength versus penetration depth is plotted. The data in Figures 17 through 19 were reduced to average unit cone load and average vane shear strength at 10-inch penetration intervals. Similar experimental data have been presented in the literature. Skempton (1951) found that the immediate bearing resistance of deep circular or square footings (the ratio of depth of footing embedment to footing width is greater than 6) on clay was approximately nine times the vane shear strength. However, actual bearing capacity failures in the field have shown this ratio may be as low as five (Lambe and Whitman, 1969), and empirical static cone penetrometer results of Begemann (1963) demonstrate that this ratio may be as high as 13.4. For similar tests on granular soils, higher ratios are expected.

Higher ratios of cone resistance to vane shear strength for granular materials is simply explained by the ratio of the sliding surfaces generated by each tool. Assuming that the shear strength of the soil is constant, the ratio of cone sliding surface to vane sliding surface is greater for granular soils than for cohesive soils. The sliding surfaces for the vane tests are cylindrical, and they are approximately the same for all soils. However, according to Figure 25, (Begemann, 1963) the sliding surfaces produced during static cone tests differ markedly for granular and cohesive soils. Begemann (1963) shows that the sliding surface produced by the cone depends upon the drainage conditions and the friction angle of the soil. A larger unit cone resistance is expected for a granular soil than for a cohesive soil, and the ratio of unit cone resistance to vane shear strength will also be proportionately larger.

The plot of the ratio of unit cone penetration resistance to maximum vane shear strength versus depth for the Site 1 sediment displays a large experimental scatter. The values range from 8.3 to 18.8 with an average value of 13.9. These values are considerably higher than the ratios presented by Skempton. However, the average agrees favorably with Begemann's results, but the scatter is rather extreme.

The data for Site 2 exhibits a very high ratio of cone resistance to vane shear strength to a depth of 10 inches. This high ratio which may be explained by the presence of a sand layer (Figure 14 and 15) approximately 15 inches deep behaves according to Begemann's theory. The ratio of cone resistance to vane shear strength for the deeper clayey silt is very consistent. The values range from 10.4 to 11.6 with an average ratio of 10.9. The values compare favorably with results of both Skempton and Begemann, and they tend to reinforce the performance accuracy of the test device.

A plot of the ratio of unit cone penetrometer resistance to peak vane shear strength versus the percent clay at the test depth is presented in Figure 25; it is an attempt to explain the scatter of data in Figure 23. The trend is toward an increasing ratio with decreasing percent clay. This trend appears reasonable because the percent clay should affect the shearing behavior of a soil. Unfortunately, there is very little data presently available to verify this relationship; however, more data are being obtained.

If this relationship can be established for ocean sediments, the static cone penetrometer will be a more economical tool than the shear vane for obtaining the "undrained" shear strength of the seafloor soils.

Sensitivity

The ratio of undisturbed vane shear strength to remolded vane shear strength for a soil sample at a constant water content is known as the sensitivity of the soil. Figure 26 presents all the sensitivity data for Site 2. Remolded vane tests were not performed at Site 1; therefore,

no sensitivity values are available for that site. An average sensitivity value of 2.5 to 3.0 was obtained for Site 2, however, erratic values of 1.3 and 8.0 were also encountered. There is no noticeable trend for sensitivity with depth. From the lines of best fit in Figures 19 and 20, the sensitivity was expected to increase with depth, however, the experimental error in the undisturbed and remolded vane shear strength values tends to mask any noticeable trend in sensitivity with depth.

The sensitivities obtained in situ (Figure 26) compare favorably with the sensitivities obtained in the laboratory vane tests (Figures 14 and 15) on cores. Sediment sensitivities of 2.5 to 3.0 were obtained for both series of tests performed on the clayey-silt (below 15 inches). In the 15-inch sandy layer at the top of the soil profile, lower sensitivities were obtained in the laboratory than in the field. This may be attributed to the different circumferential (not rotational) shear rates used in the laboratory and field for the two different soils. It was initially believed that different sensitivities might be obtained in the laboratory and field because of the different remolding techniques. Terzaghi and Peck (1967) state that "the degree of disturbance caused by rotating a vane differs from that caused by kneading a sample in the laboratory". The numerical values of sensitivity determined by the two procedures may, therefore, differ, but the magnitude of difference is unknown. The experimental error for the tests performed in situ and in the laboratory were not sufficient to note any significant trends.

SUMMARY AND CONCLUSIONS

1. DOTIPOS, with the vane shear and cone penetrometer tower, operates satisfactorily to water depths of 600 feet.

2. Several sets of vane shear tests and several cone penetration tests can be performed in an eight-hour work day.

3. Load handling of DOTIPOS from a Navy ARS or a Navy LST posed no problem when the wave height was less than 5 feet.

4. Vane shear and cone penetrometer test results, when compared to previous theoretical and experimental results, appear reasonable.

5. Reasonable agreement exists between laboratory and in-situ vane shear data for Sites 1 and 2; however, the in-situ strengths slightly exceed the laboratory strengths. The disagreement most likely stems from errors in the laboratory test results generated by soil disturbance which originates from poor sampling techniques.

6. A relationship between sediment clay content and the ratio of cone resistance to vane shear strength appears feasible for seafloor sediments. If this relationship can be established, the cone penetrometer will become a more useful and economical tool in support of a seafloor investigation.

The DOTIPOS-mounted vane shear and cone penetrometer testing apparatus shows considerable potential for providing the Navy design engineer with an efficient, reliable, and effective means of evaluating some sediment engineering properties with which to design seafloor foundations.

FUTURE WORK

Current plans call for the continued evaluation of the vane shear and cone penetrometer apparatus and the performance of checkout tests on a DOTIPOS-mounted piston corer, capable of obtaining a relatively undisturbed sample to 10 feet in the seafloor. Seafloor tests will be performed at 100-, 600-, 1200-, and 6000-foot test sites. In addition, DOTIPOS with the vane shear and cone penetrometer tower and 10-foot piston corer will be used for another NCEL test program to gather cores and in-situ shear strength data. The cores and in-situ shear strength data will be used for a detailed investigation of sample disturbance and shear strength development.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the participation of Mr. T. R. Kretschmer for his efforts in the development and evaluation of DOTIPOS and the vane shear and cone penetrometer device. He also provided the data presented in this report. Mr. J. Padilla functioned as cruise leader during sea operations and capably controlled all phases of the handling of DOTIPOS. Also, Mr. P. Babineau and Mr. F. Nelson exhibited high degrees of competency in the operation and maintenance of DOTIPOS.

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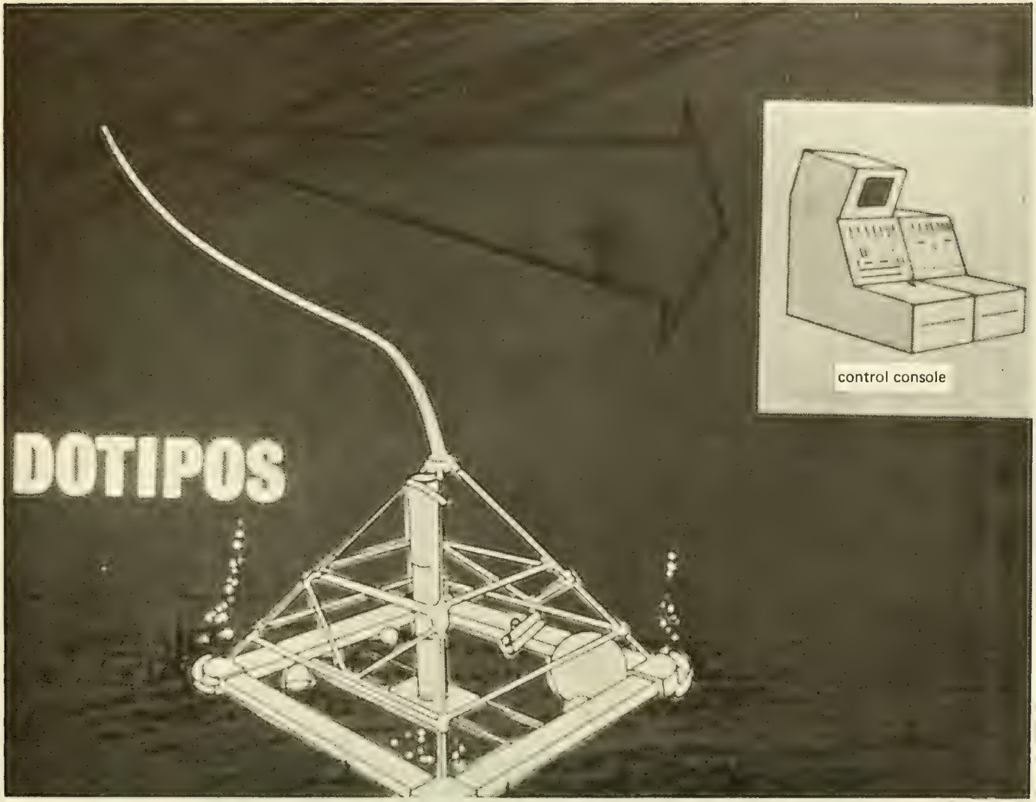


Figure 1. Simulation of DOTIPOS operation.

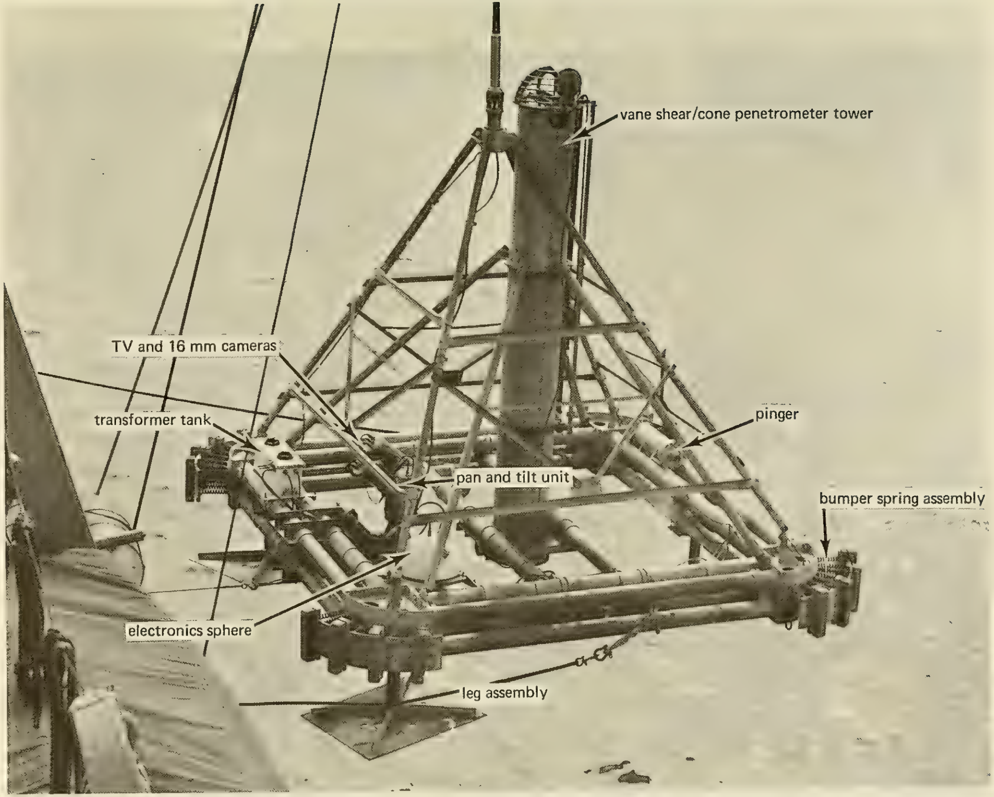


Figure 2. DOTIPOS platform with vane shear and cone penetrometer tower.

Figure 3. Control instrumentation for DOTIPOS components.

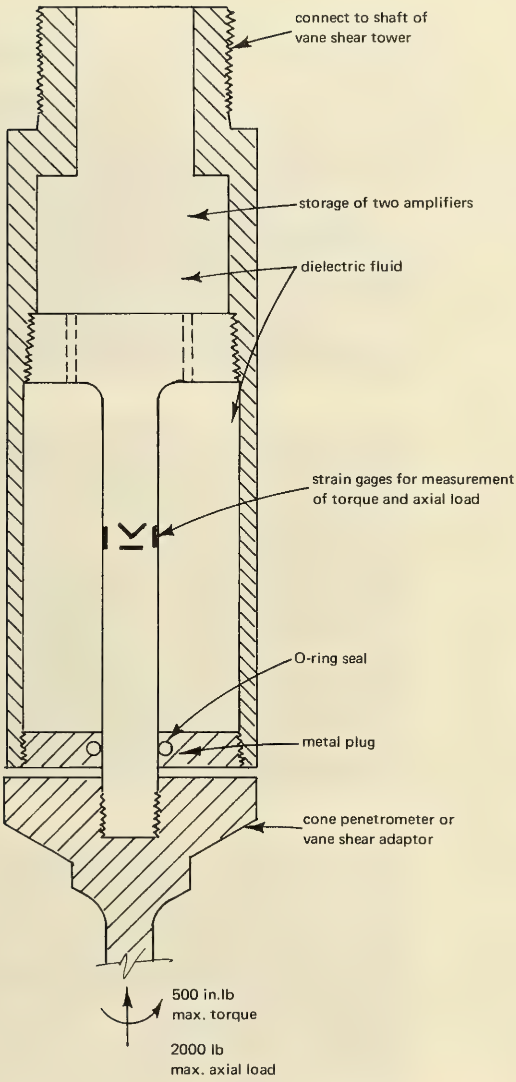
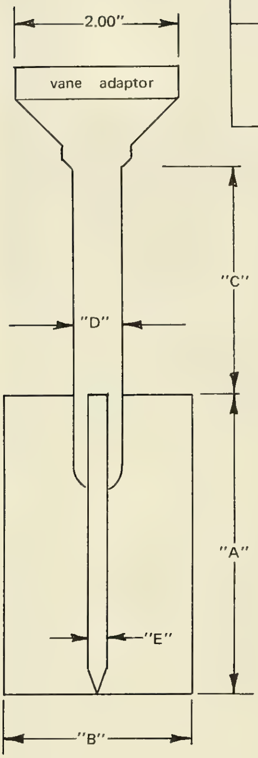


Figure 4. Cross-section of load cell (not to scale).

Vane Shear Tabulation					
Vane No.	"A"	"B"	"C"	"D"	"E"
1	4"	2"	6.45"	.375"	.05"
2	5"	2½"	6.40"	.438"	.062"
3	6"	3"	6.17"	.438"	.090"
4	8"	4"	6.10"	.500"	.112"



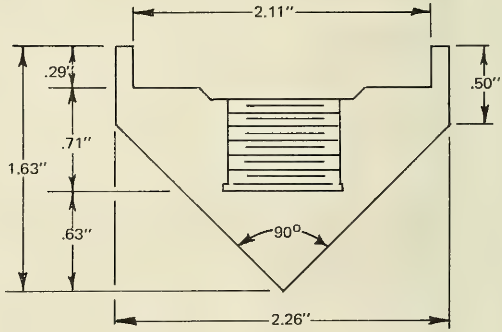
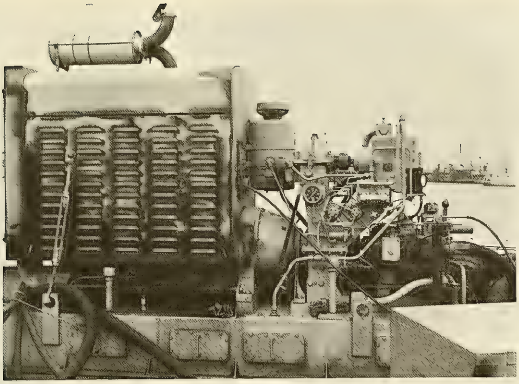
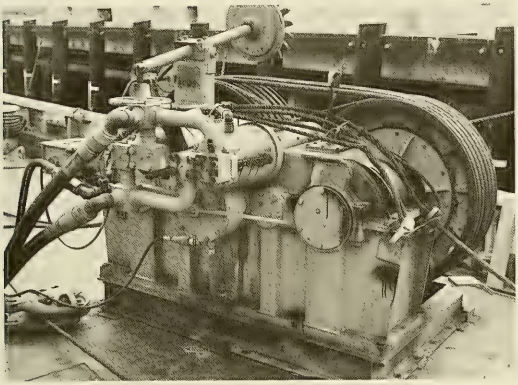


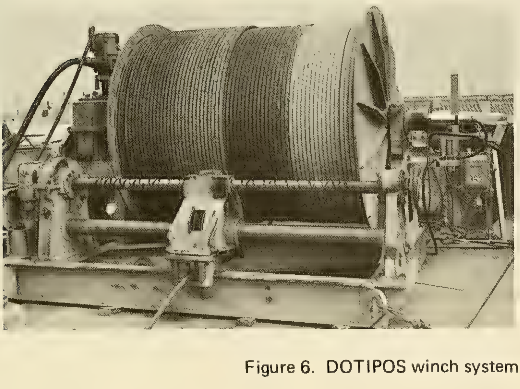
Figure 5. Specifications for cone penetrometer and vane shear assembly with adaptor. (Not to scale)



a. Power unit.



b. Dual-drum traction unit.



c. Drum storage unit

Figure 6. DOTIPOS winch system.

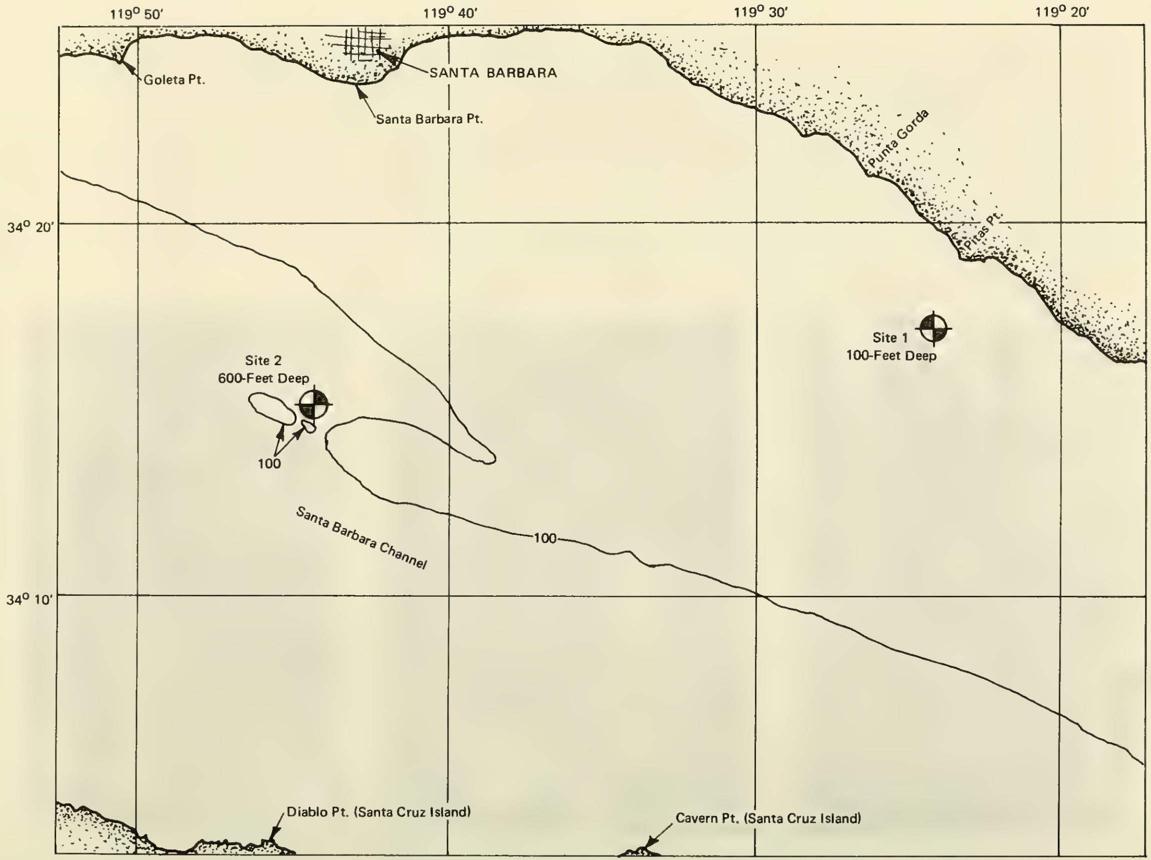


Figure 7. Location of test areas (contours in fathoms).

Figure 8. Cone penetrometer tool in test ready position on ship's deck.

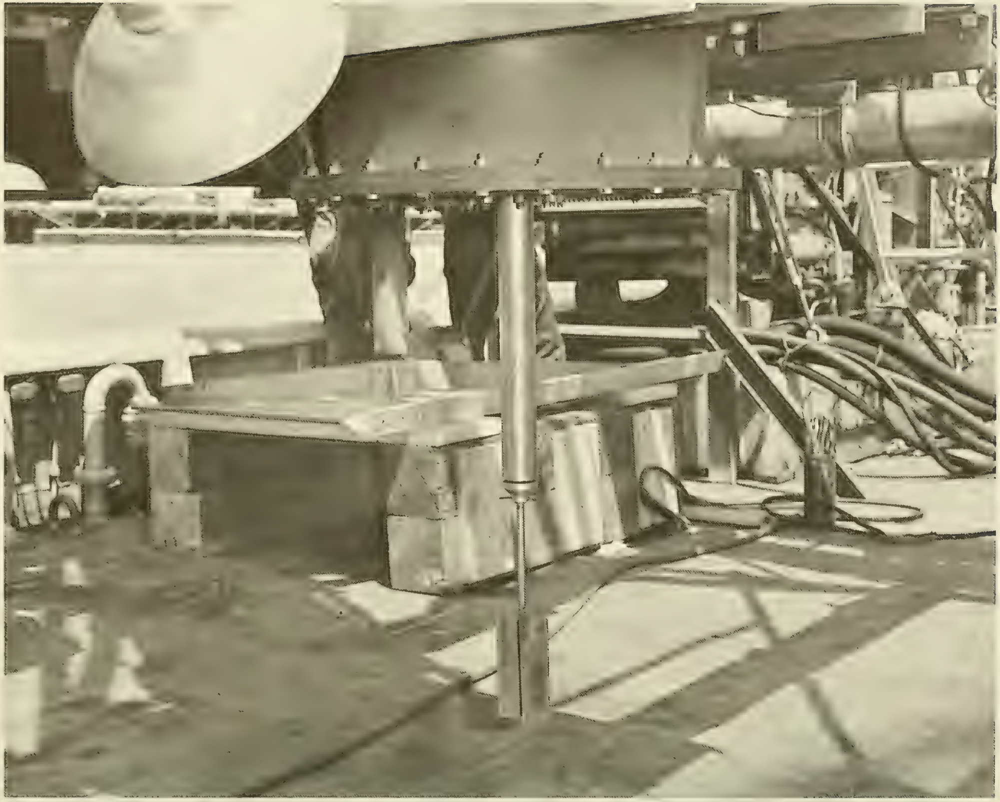


Figure 9. Vane shear tool in test ready position on ship's deck.

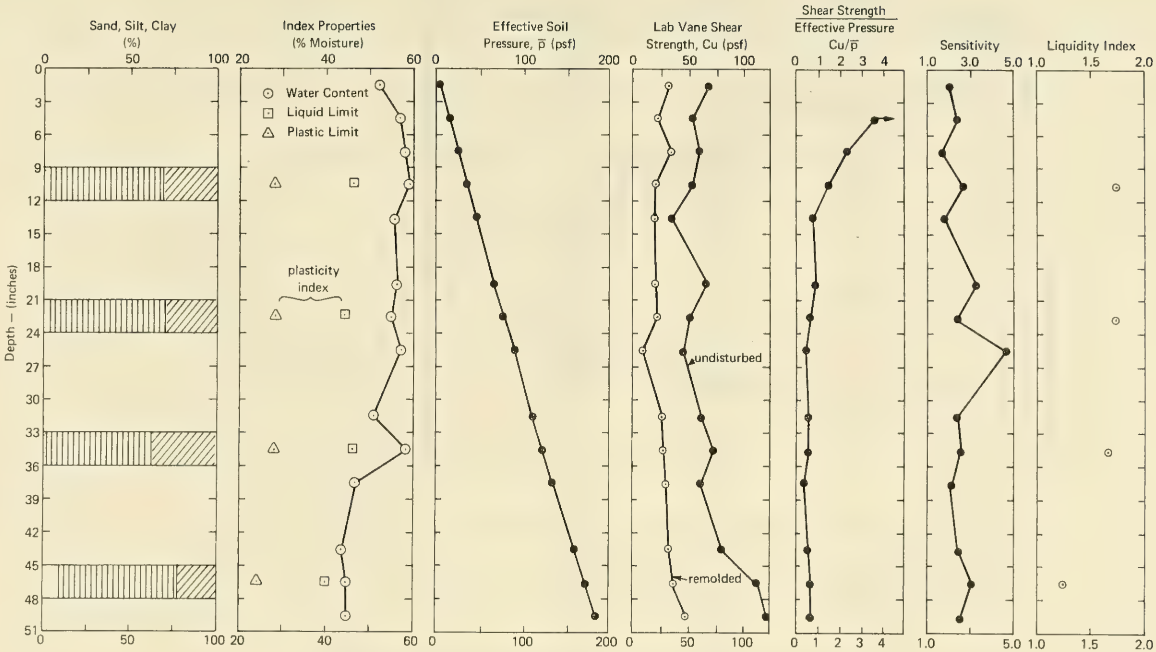


Figure 10. Soil Properties for Site 1 — core no. PP-1.

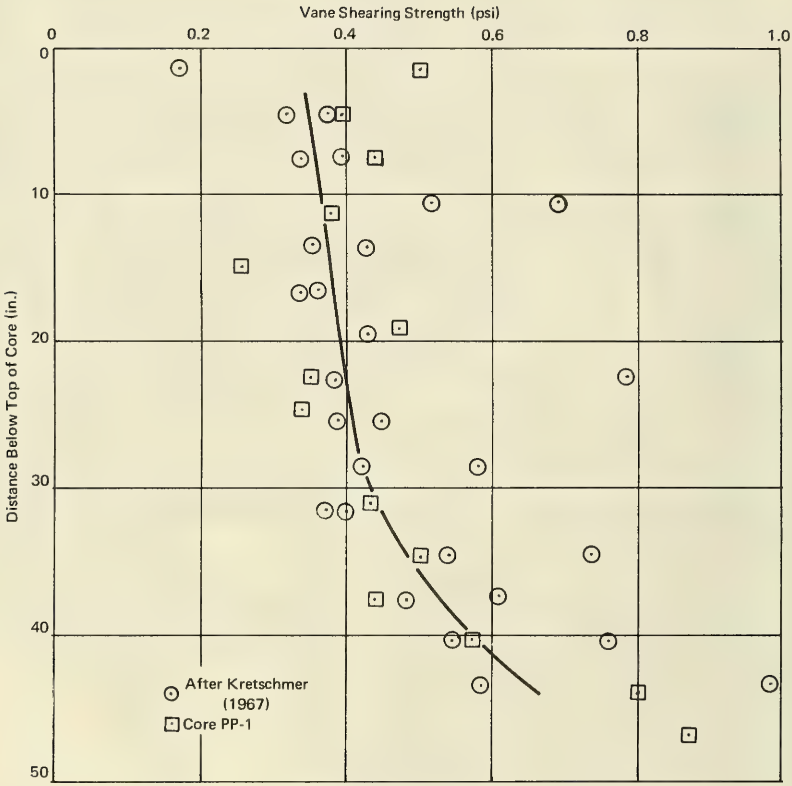


Figure 11. Average vane shearing strength versus depth — Site 1.

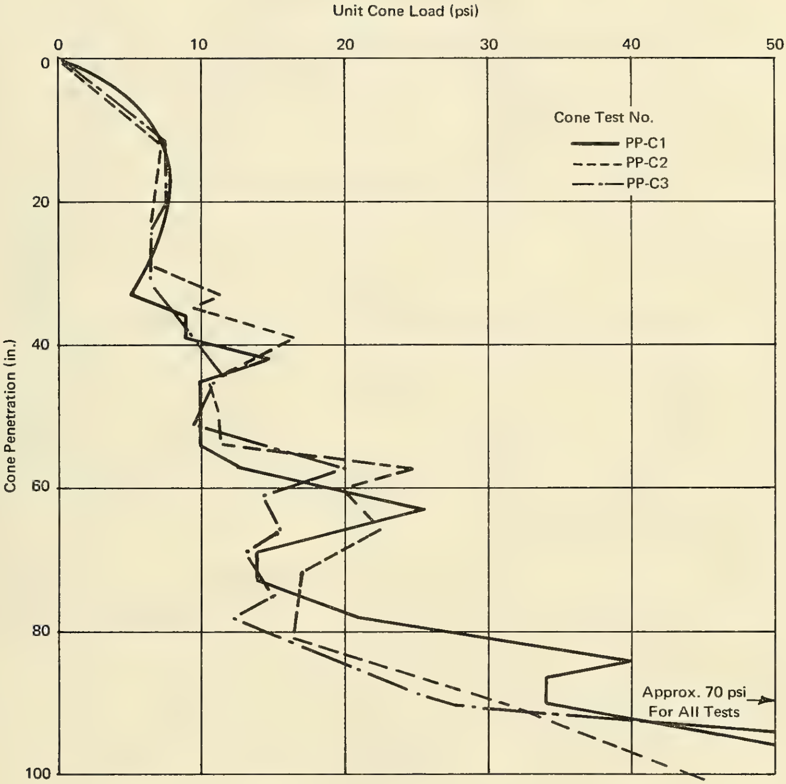


Figure 12. Unit cone load versus cone penetration for Site 1 sediment.

Figure 13. In-situ vane shear strength versus vane penetration for Site 1 sediment.

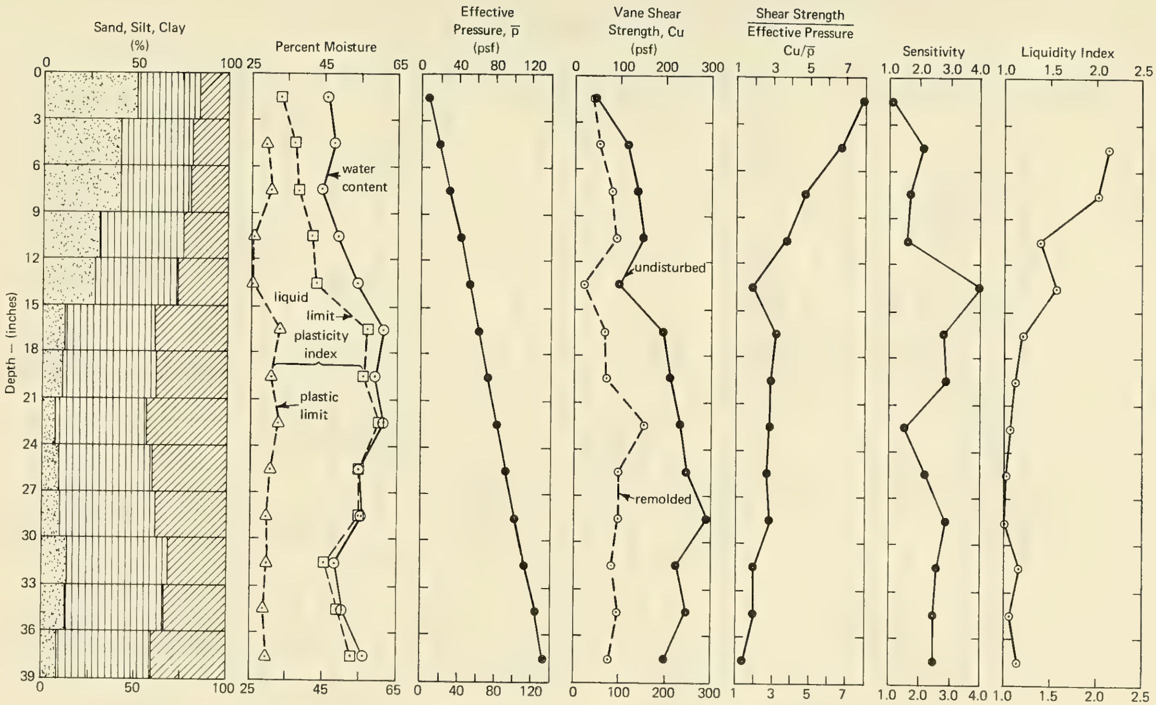


Figure 14. Soil Properties for Site 2 — core no. SCNI-37.

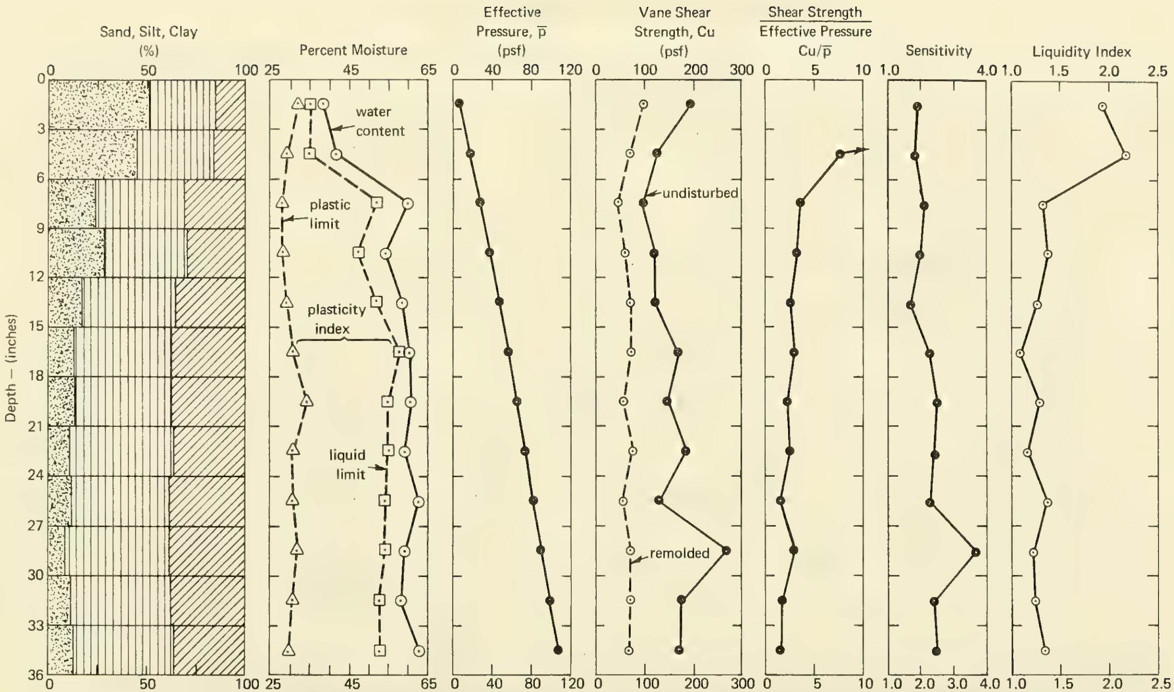


Figure 15. Soil Properties for Site 2 — core no. SCN1-49.

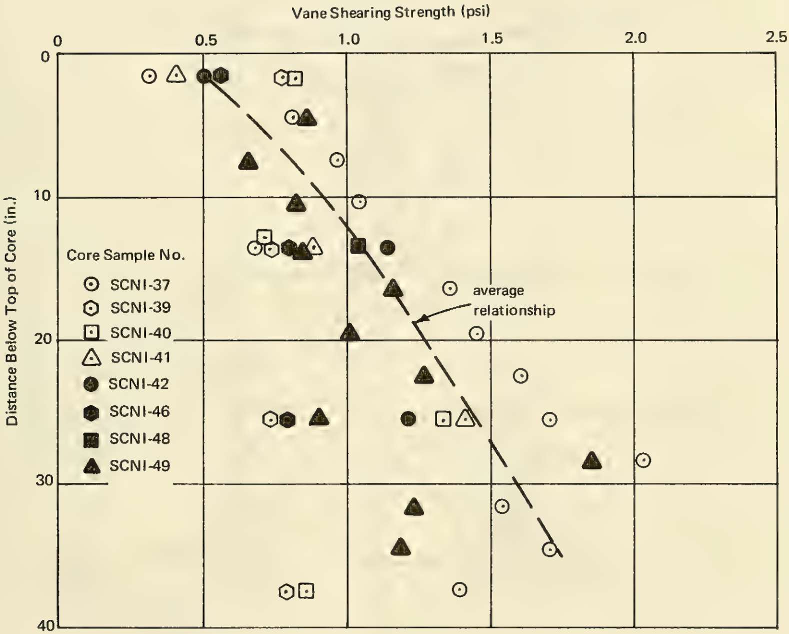


Figure 16. Average vane shearing strength — Site 2.

Figure 17. Unit cone load versus cone penetration for Site 2 sediment.

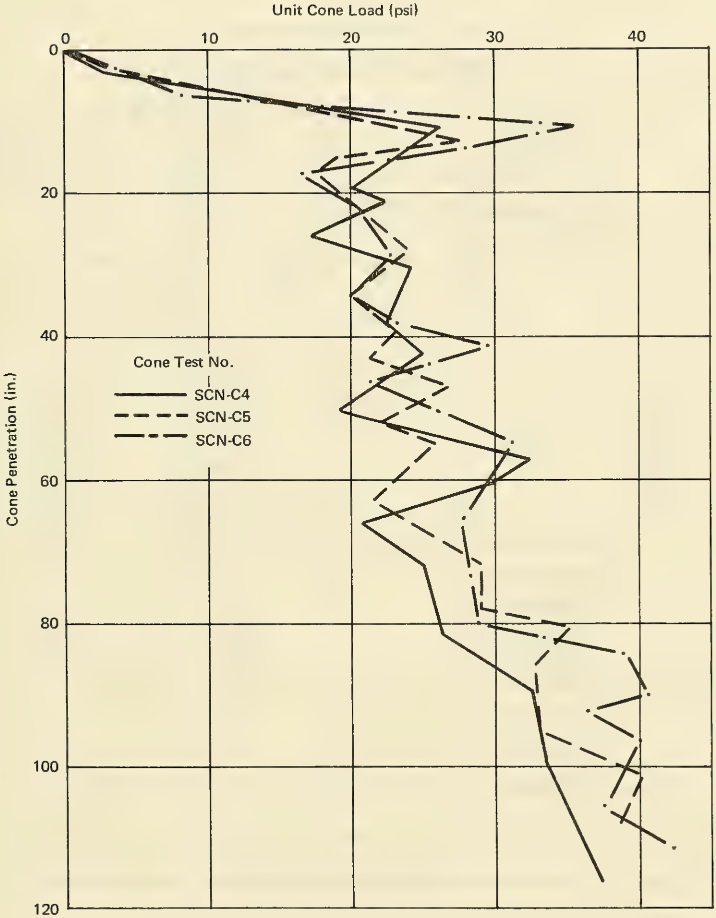


Figure 18. Unit cone load versus cone penetration for Site 2 sediment.

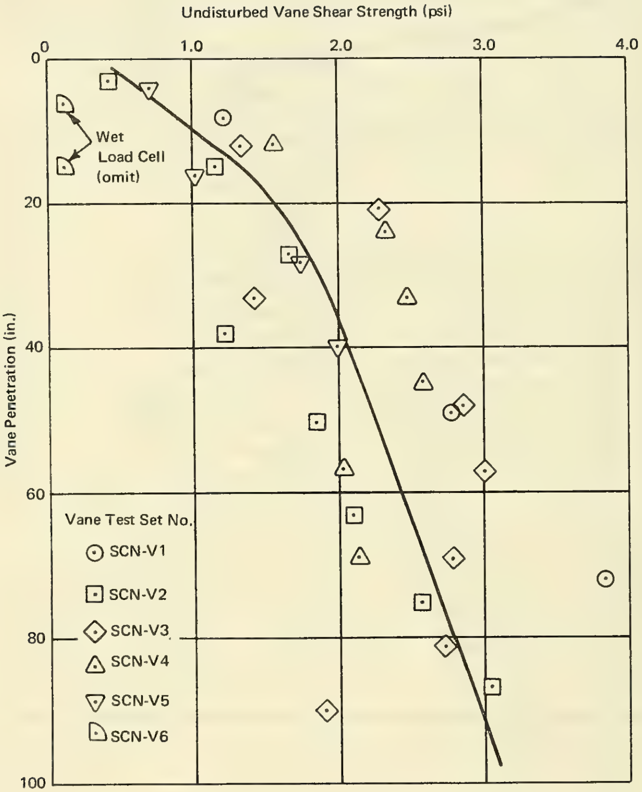


Figure 19. In-situ vane shear strength versus vane penetration for Site 2 sediment.

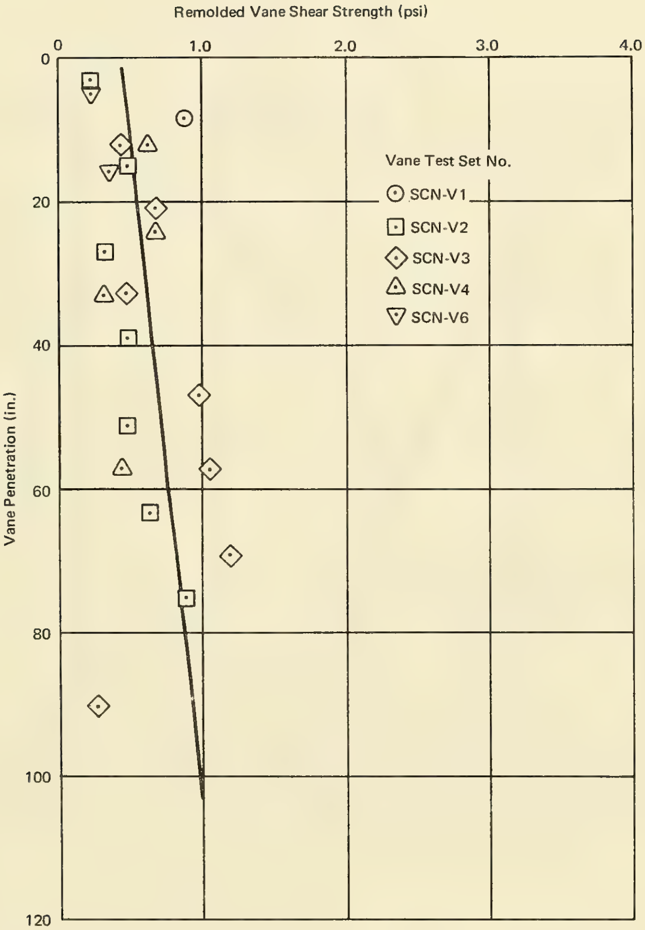


Figure 20. Remolded vane shear strength versus vane penetration for Site 2 sediment.

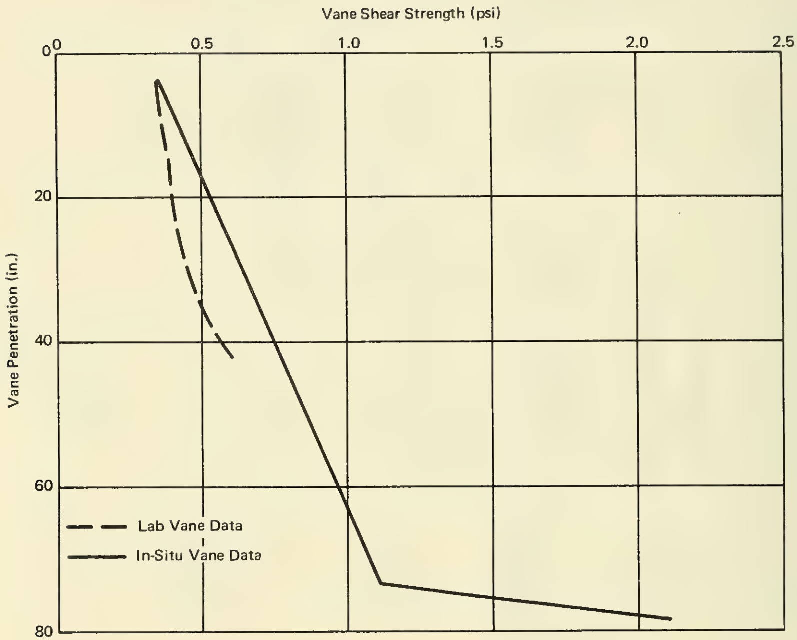


Figure 21. Comparison of laboratory vane shear data with in-situ vane shear data for Site 1 sediment.

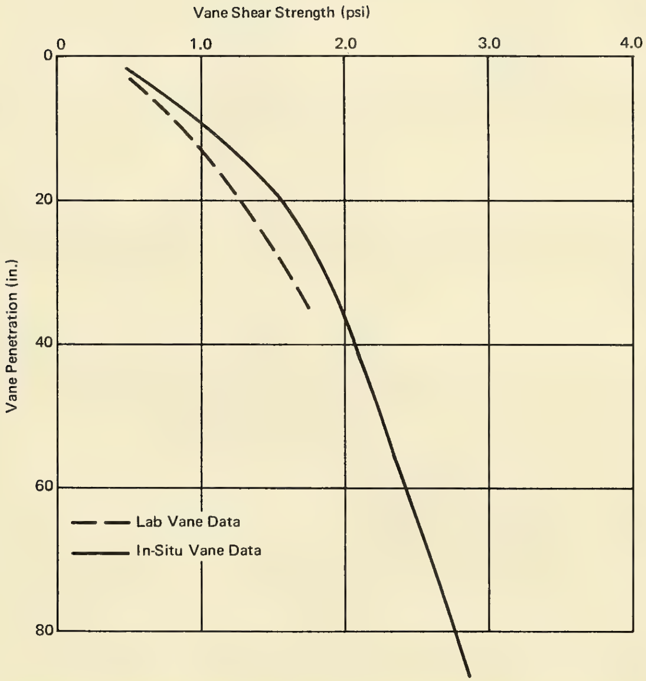


Figure 22. Comparison of laboratory vane shear data with in-situ vane shear data for Site 2 sediment.

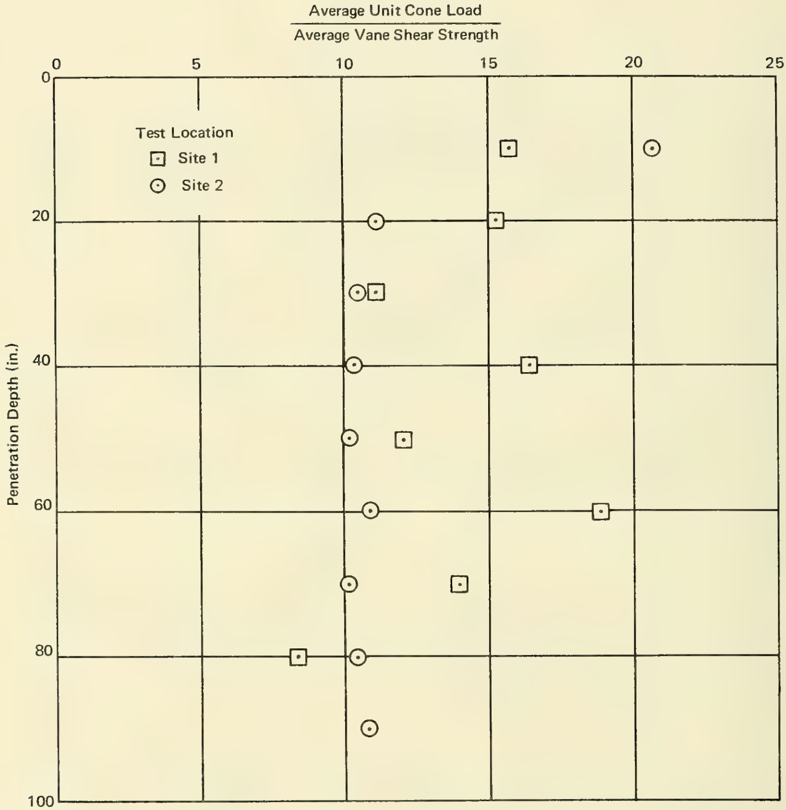


Figure 23. Relationship between the ratio of average unit cone load to average vane shear strength and penetration depth for Site 1 and Site 2 sediment.

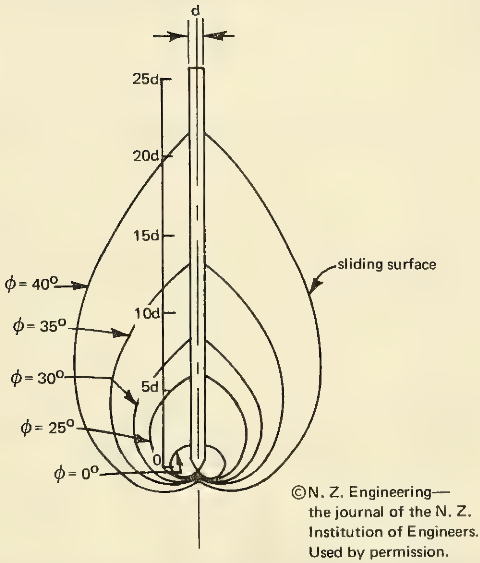


Figure 24. Theoretical sliding surfaces (From Begemann, 1963).

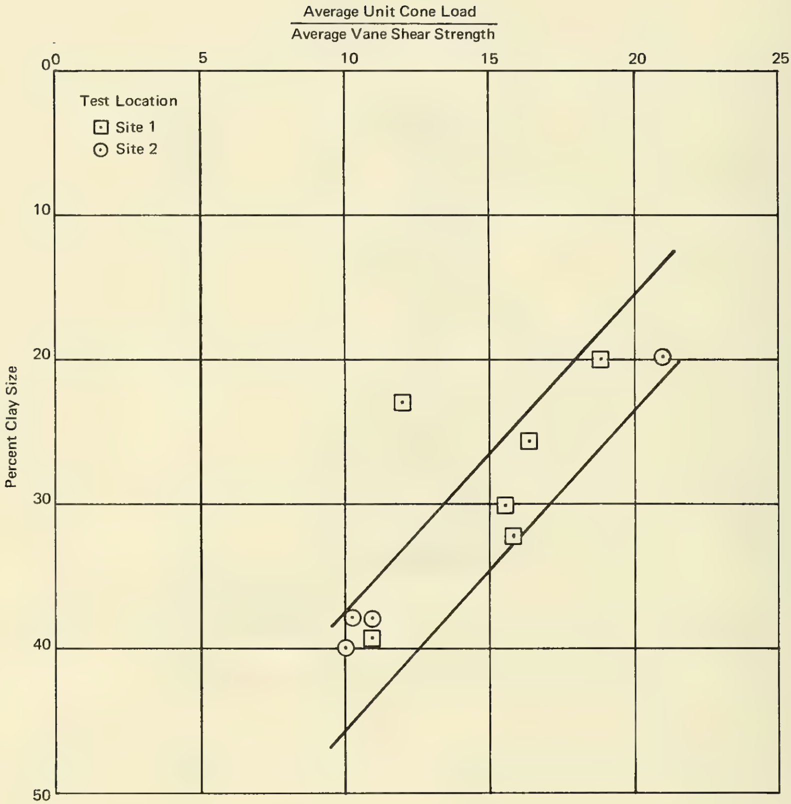


Figure 25. Relationship between the ratio of the average unit cone load to average vane shear strength and the percent clay size for Site 1 and Site 2 sediment.

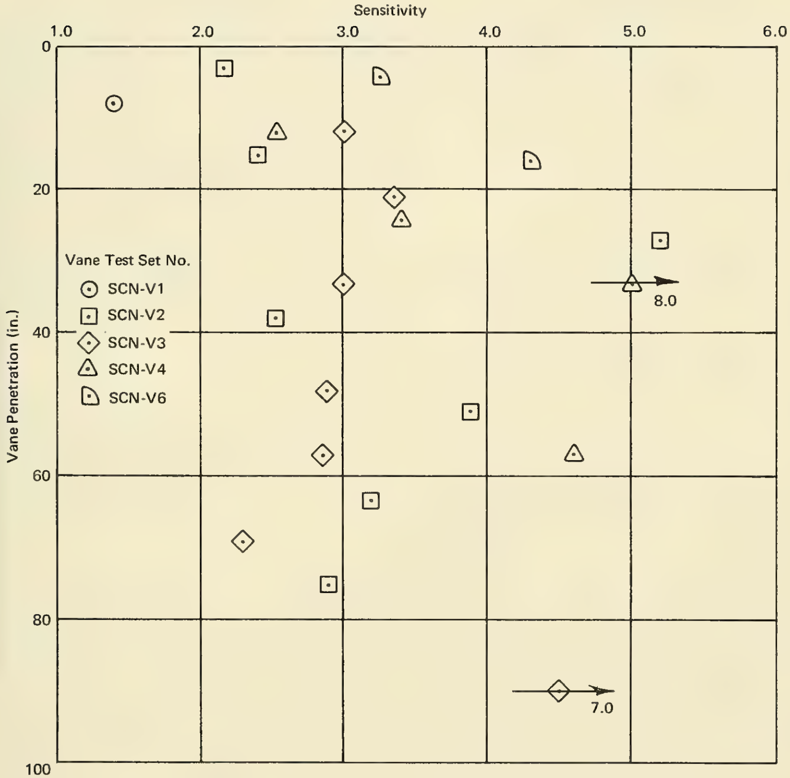


Figure 26. Relationship between sensitivity and vane penetration for Site 2 sediment.

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13. ABSTRACT

The Naval Civil Engineering Laboratory (NCEL) has developed a vane shear and cone penetrometer apparatus capable of obtaining the in-place undrained shear strength of sediments to a depth of 10 feet in the seafloor. The device is a subsystem of the Deep Ocean Test In-Place and Observation System (DOTIPOS). Information obtained with this equipment will enhance the Navy's ability to design foundations more economically and reliably for seafloor installations. The results of tests performed at 100- and 600-foot deep sites and the evaluation of DOTIPOS and the vane shear and cone penetrometer apparatus are presented.

The DOTIPOS-mounted vane shear and cone penetrometer apparatus operates satisfactorily to water depths of 600 feet and produces results which appear reasonable when compared to previous theoretical and laboratory experimental results. Laboratory and in-situ vane shear results are in reasonable agreement; however, the in-situ results exceed the laboratory results by 10 to 20 percent. A relationship between percent clay content of the sediment and the

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ratio of cone resistance to vane shear strength appears feasible for seafloor sediments. Verification of this relationship will establish the cone penetrometer as a more useful and economical site survey tool.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Performance tests						
Measuring instruments						
Measurement						
Shear strength						
Cone penetrometer						
Sediments						
Ocean bottom						
In situ						
Vane shear tests						
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